RAW MATERIALS

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AIR CLASSIFICATION OF SANDS FOR THE GLASS INDUSTRY

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The process of air classification of substandard sands is discussed. It is demonstrated that via an optimum selection of separation boundaries for classifying equipment it is possible to obtain sand, whose granulometric composition meets the state standard requirements. A mathematical model is developed, which makes it possible to optimize the operating parameters of air classifiers and to obtain a maximum output of finished product. Examples of industrial use of air classifiers are given, which confirm the expediency of using air classification of sands in the glass industry.

Quartz sands used in the glass industry should satisfy the requirements of GOST 22551–77, which regulates the mineralogical, chemical, and granulometric compositions. According to this standard, the granulometric composition of sand has to satisfy two requirements: the content of particles larger than 0.8 mm should not exceed 0.5%, and that of particles below 0.1 mm should not exceed 5.0%.

Many enterprises use sand that is substandard regarding its granulometric composition, in which the content of the fraction above 0.8 mm exceeds 0.5%. To bring such sand to standard requirements, screen sifting is used on sieves with cell size 0.8 mm and in some cases, 1.0 mm. Substandard sand containing over 5% fraction below 0.1 mm is not acceptable for production, as it is technically and economically inadvisable to implement sifting on a sieve with the cell size below 0.1 mm. The output of a sieve with cell size 0.1 mm and surface area 3 m^2 is only 0.5 ton/h. Furthermore, fine-sized sieves have low mechanical strength and have a tendency to clogging of cells. It should be noted that any sifting requires a special aspiration system.

However, these problems can be solved by using air classification, whose main advantages are as follows:

– high separation efficiency;

– a wide range of separation boundaries and simplicity in controlling the particle size in the finished product;

– a wide output range (from several kilos per hour to hundreds of tons per hour);

– low energy consumption (on the average 1 – 2 (kW · h)/ton);

– the classifiers operate in rarefied medium and satisfy environmental requirements.

The practical experience of concentration works in other countries shows that the most effective application area for air classifiers is separation along the boundary ≤ 1 mm. Within this range, classifiers are much more efficient than screens. Unfortunately, such air classifiers are not industrially produced in our country. However, more than 50 various modifications of air classifiers have been developed at the Ural State Technical University and patented (including patents in West Germany, England, France, and Italy). Furthermore, these types of classifiers have been extensively implemented in various sectors of industry. The air classification of molding sand for foundry is the best suited for the considered purposes. The first implementation of an air classifier in glass production took place in 2000 at the Kavminsteklo JSC.

In view of the relative novelty of air classification in glass production, we find it expedient to consider in more detail the theoretical principles of this process. It should be noted that the problem of optimization of classifier performance can be reduced to determination of necessary separation boundaries, which, on the one hand, would satisfy the prescribed granulometric composition requirements and, on the other hand, would ensure maximum yield of the finished product.

The granulometric composition of sand for glass production is determined by sieve analysis; therefore, it can be conveniently interpreted using the notion of an arithmetic vector. An arithmetic vector is an ordered set of elements. In our case the component r_i of the vector $\vec{r}$ (r_1, r_2, ..., r_i, ..., r_n) is the particular residue on the ith sieve. The number of sieves,

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and, accordingly, the number of narrow size classes, is equal to n. It follows from the norm condition that

$$\sum_{i=1}^{n} r(x_i) = 100\%.$$

The most significant parameter of air classifiers is the function of the degree of fractional extraction.

The function of the degree of fractional extraction of the fine product of screening $F_f(x_i)$ is the share of particles of the narrow size class x_i extracted as the fine product. Such a function is graphically represented as a fractional screening curve (Fig. 1): it is often called the "Tromp curve" abroad.

Similarly, the degree of fractional extraction of the coarse product of screening $F_c(x_i)$ is the share of particles of the narrow size class x_i extracted as the coarse product:

$$F_f(x_i) + F_{cf}(x_i) = 100\%.$$

The size of particles which are extracted equally (50% each) in the fine product and in the coarse product is accepted as the separation boundary x_{50}.

The functions of the degree of fractional extraction of product of a narrow size class have wide applications, since they have a number of important properties. Their main property is that they are independent of the granulometric composition of the initial material. The function of the degree of fraction extraction depends only on the equipment design and the separation boundary, to which the equipment is adjusted [1, 2]. There are various functions and analytical dependences which can be used to approximate the function of the degree of fractional extraction for a specific classifier. In the present study we are going to used the Plitt function:

$$F_f(x_i) = \frac{100}{1 + \left(\dfrac{x_i}{x_{50}}\right)^p},$$

where x_i is the size of the product of a narrow size class, mm; x_{50} is the separation boundary, mm; p is a dimensionless parameter characterizing the sharpness of separation.

The steeper the curve, the more efficient is the equipment. Figure 1 shows the fractional screening curve for an ideal equipment. It is a step function. Thus, all particles (100%) sized x_i smaller than x_{50} should be extracted as the fine product, and particles of a size larger than x_{50} should constitute 0%. However, real classifiers have S-shaped curves. There are various criteria for separation sharpness (efficiency) that characterize the degree of approximation of the real curve to the step function. One of the most common criteria is the Eder – Maier efficiency parameter:

$$E = 100 \frac{x_{75}}{x_{25}},$$

where x_{75} and x_{25} are the sizes of particles that are extracted as fine separation product, in the amount of 75 and 25, respectively.
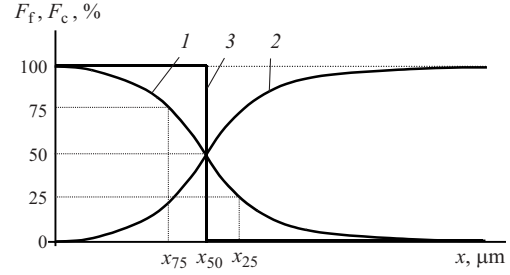
Fig. 1. Fractional separation curves: *1*, *2*, and *3*, respectively, indicate the degree of fractional extraction in the form of fine product $F_f(x_i)$, coarse product $F_c(x_i)$, and in the case of an ideal classifier.

It is easy to deduce the relationship between the parameter p and the Eder – Maier parameter:

$$E = 100 \left(\frac{1}{9}\right)^{1/p}.$$

If the granulometric composition of the initial sand is known, the results of air classification can be fully calculated knowing the function of the degree of fractional separation, i.e., it is possible to estimate the shares of the coarse and fine separation products and their granulometric compositions. Thus, the yield of fine G_f and coarse G_c separation products can be found from the dependences

$$G_f = \frac{1}{100} \sum_{i=1}^{n} r(x_i) F_f(x_i);$$

$$G_c = 100 - G_f.$$

The granulometric compositions of the fine r_f and coarse r_c separation products can be calculated as follows:

$$r_f(x_i) = \frac{r(x_i) F_f(x_i)}{G_f};$$

$$r_c(x_i) = \frac{r(x_i)[100 - F_f(x_i)]}{G_c},$$

where $i = 1, 2, 3, ..., n$.

Let us consider the problem of optimum control of the air classification process using a specific example. Table 1 shows the averaged granulometric compositions r_i of substandard sands (screenings) from the Gora Khrustal'naya deposit. Practical experience shows that the fraction content of narrow size classes is not constant and may vary within a certain limit. Therefore, Table 1 indicates the bottom $r^b(x_i)$ and upper $r^u(x_i)$ variation limits for the granulometric composition of the initial sand.

It can be seen that the granulometric composition does not meet the state standard requirements. Thus, the content of fractions above 800 μm is 4.4%, and the content of fractions below 100 μm is 6%. The fine fractions usually contain an argillaceous component. The performed analysis of the
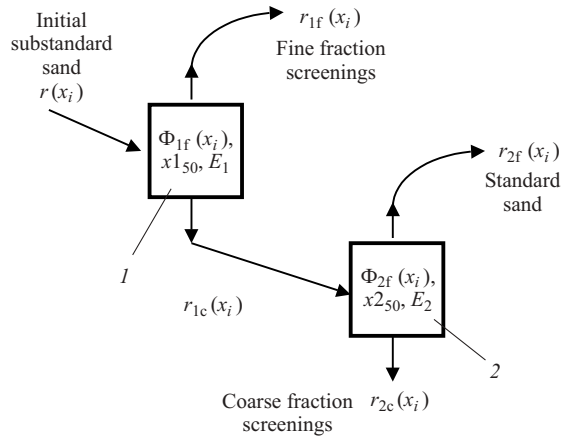
Fig. 2. Technological scheme of substandard sand treatment: *1* and *2* are, respectively, classifiers of the first and the second stage.

sands confirmed this assumption. Therefore, it is advisable to bring down the content of the fine class fractions not to 5%, as required by the standard, but to 0.5%. In this case the sand becomes concentrated.

Thus, to bring sand to the required conditions, a two-stage classification for both fine and coarse boundaries is necessary, in order to eliminate an excess of coarse and fine fractions. The sand treatment scheme is shown in Fig. 2 and includes the classifiers of the first and the second stage.

The first separation stage classifier has the separation efficiency E_1 and is adjusted to the separation boundary $x1_{50}$. The second separation stage classifier has the separation efficiency E_2 and is adjusted to the separation boundary $x2_{50}$. The degree of fractional separation for each classifier is described using two parametric Plitt functions:

$$\left.\begin{aligned} F_{1f}(x_i) &= \frac{100}{1+\left(\dfrac{x_i}{x1_{50}}\right)^{p1}}; \\ F_{2f}(x_i) &= \frac{100}{1+\left(\dfrac{x_i}{x2_{50}}\right)^{p2}}. \end{aligned}\right\} \quad (1)$$

TABLE 1

i	x_i, μm	$r(x_i)$, %	$r^b(x_i)$, %	$r^u(x_i)$, %
1	0	1.7	1.0	2.5
2	50	0.5	0.3	0.8
3	63	3.8	2.0	6.0
4	100	3.3	2.0	5.0
5	160	6.0	4.0	8.0
6	200	19.1	15.0	22.0
7	315	16.9	12.0	20.0
8	400	35.9	30.0	41.0
9	630	8.4	6.0	10.0
10	800	3.8	2.0	6.0
11	1600	0.6	0.3	1.0

Then, the granulometric composition of standard sand $r_{2f}(x_i)$ can be found from the dependence:

$$r_{2f}(x_i) = \frac{r(x_i)[100-F_{1f}(x_i)]F_{2f}(x_i)}{\sum\limits_{i=1}^{n} r(x_i)[100-F_{1f}(x_i)]F_{2f}(x_i)}. \quad (2)$$

In accordance with the specified requirements imposed on the granulometric composition of sand, the content of the fine and coarse fractions should not exceed 0.5%, i.e., the following inequality should be satisfied:

$$\sum_{i=1}^{3} r_{2f}(x_i) \le 0.5; \quad \sum_{i=10}^{11} r_{2f}(x_i) \le 0.5. \quad (3)$$

The granulometric composition of initial material is accidental and may vary within the limits

$$r^b(x_i) \le r(x_i) \le r^u(x_i). \quad (4)$$

The target functions will be taken as the yield of acceptable product, which should be maximum:

$$G_a = \sum_{i=1}^{11} r(x_i)[100-F_{1f}(x_i)]F_{2f}(x_i) \rightarrow max. \quad (5)$$

Thus, target function (5), Eqs. (1) and (2), and inequalities (3), (4) comprise a mathematical model. The problem is reduced to determining the required separation boundaries $x1_{50}$ and $x2_{50}$ that would ensure a maximum target function for the specified restrictions. Since the target function, the equations, and the inequalities are nonlinear, one obtains a nonlinear programming problem.

Such problems are solved using different numerical methods, for instance, conjugate gradient, the Newton method, configuration method, etc. In the case of a determined composition, this problem can be solved using "Solution Search" command in Excel. However, in our case the problem is complicated not only by the presence of restrictions, but also by the fact that the vector of the initial granulometric composition is random. Therefore, we will solve this problem by the simulation modeling method using the following algorithm.

At the first stage, we generate one hundred random vectors of granulometric composition of the initial sand satisfying the system of equations (4). Then the nonlinear problem, i.e., search for the maximum target functions for the specified restrictions, is solved for each composition. The solution results (values of separation boundaries and output of separation products) are stored in the database. The database is next processed to find the mean values (mathematical expectations) of the parameters and their mean quadratic deviations.

Since the initial composition is random, the solution found has a probabilistic nature. In order to determine the probability of solving the problem, the parameters are estimated for fixed separation boundaries for each of 100 ran-
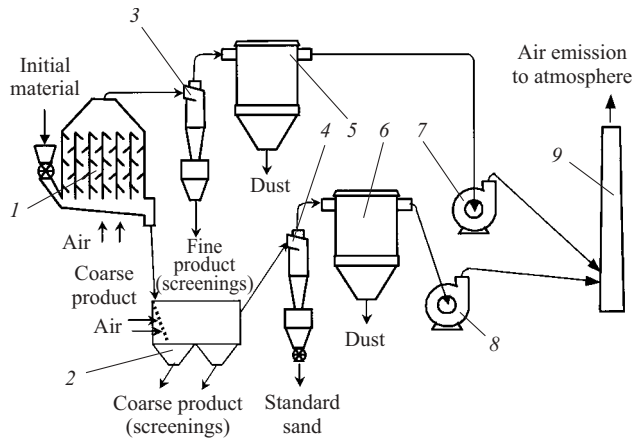
Fig. 3. Diagram of equipment for air classification of substandard sand.

dom compositions. The probability equation represents the confidence level of the solution found.

This algorithm for the initial data listed in Table 1 has been implemented in Microsoft Visual Basic. The classifier efficiency in the calculations was accepted as $E_1 = E_2 = 72\%$. Thus, the separation boundaries $x1_{50} = 120\ \mu m$ and $x2_{50} = 800\ \mu m$ provide for 82.9% yield of the finished product and the probability of a solution equal to 93%. It follows from the physical meaning of the problem that to increase the probability of a solution, it is necessary to increase $x1_{50}$ and to decrease $x2_{50}$. However, in this case the output of the finished product will be reduced. In fact, the separation boundaries $x1_{50} = 125\ \mu m$ and $x2_{50} = 790\ \mu m$ ensure 82.8% yield of the finished product and 100% solution probability. As the yield in this case decreases insignificantly, the latter variant is preferable.

Figure 3 shows the diagram of equipment for air classification of substandard sand. The equipment includes a multi-row gravity classifier *1* for separation along the fine-fraction boundary, a lateral-flow classifier *2* for separation along the coarse-fraction boundary, cyclones *3* and *4* for separation of sand from air, sleeve filters *5* and *6* for sanitary purification of air, fans *7* and *8* generating air flow in the classifiers, and a pipe *9* for releasing purified air to the atmosphere.

In accordance with the specified scheme, all the main equipment units, i.e., classifiers, cyclones, and sleeve filters, operate in a rarefied atmosphere developed by fans. This prevents dust emission to the work zone and improves the sanitary and environmental parameters of production.

The problem can be simplified if the initial sand is substandard only with respect to the coarse fraction, or only with respect to the fine fraction. In this case one-stage separation should be implemented. The method for determining the optimum separation boundary is the same.

To implement separation by coarse-fraction boundaries, it is recommended to use lateral-flow air classifiers with a slanting louver grate. Thus, the air classifier used at the Kavminsteklo JSC sands for separation with an output of 20 tons/h has dimensions $2.0 \times 0.35 \times 1.5$ m.

To implement separation by coarse-fraction boundaries, it is recommended to use gravity cascade air classifiers. Such equipment for dry concentration of molding sands is used at the Balasheiskii Concentration Works. The classifier is intended for separation along the boundary $80 - 100\ \mu m$. For an output of 20 tons/h, its cross-sectional area is 1.9×0.4 m, and its separation sharpness is 75%.

The industrial experience demonstrated that air classification of glass sand is promising and makes it possible to bring substandard sand at low cost to the level required by the state standard.

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